Technical Note

Modeling and Test Data Uncertainty Factors Used in Prior FEMA P695 Studies

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Abstract: This technical note presents findings from a study investigating the correlation between the number of test data available and the choice of the uncertainty factors (called beta) used in the FEMA P695 methodology to quantify the quality of test data and modeling. On the basis of reviewing data from the existing literature on past FEMA P695 studies, an attempt was made to assess if there exists a trend in the choice of beta factors for new structural systems. This study can help in better estimating the test data (β_{TD}) and modeling (β_{MDL}) uncertainty factors for a new structural system with the available test data. **DOI: 10.1061/(ASCE)ST.1943-541X.0002906.** *© 2020 American Society of Civil Engineers.*

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Introduction

For the last decades, seismic performance factors have been prescribed by various codes and standards (e.g., ASCE 7) for the design of lateral load resisting systems. For various structural systems, these values have been established based on judgment and qualitative comparison of the widely used systems present at that time. In 2009, FEMA published the FEMA P695 (FEMA 2009) methodology, based on the Applied Technology Council (ATC)-63 work, that aimed to provide a rigorous basis to quantitatively determine values of the building seismic performance factors, anchoring these values on results from series of incremental dynamic analyses using nonlinear time history analyses for a large number of ground motions.

The methodology relies on creating nonlinear models to represent the actual behavior of the system for a range of archetypes and explicitly considering uncertainties in the ground motions, modeling, design, and test data that are used in the nonlinear analysis. In order to determine the seismic performance factors for the design of new seismic force-resisting systems, the methodology requires that the aforementioned uncertainties be evaluated. A key aspect of the FEMA P695 procedure is that it relies on expert opinion to assess uncertainty factors *ratings* (from *poor* to *superior*) that will be used to determine acceptable margins against collapse from the results obtained by the FEMA P695 methodology.

As the choice of uncertainty factors given in the FEMA P695 methodology is subjective and specific to the lateral system under consideration, understanding the variations of these uncertainty factors can help in a better estimation of the adjusted collapse margin ratio (ACMR) and, hence, the seismic performance factors of lateral load resisting systems. Further, finding a correlation between the uncertainty factors selected in past FEMA P695 projects and the number of experimental studies conducted on the system can help minimize the number of tests required for a new system to determine appropriate performance factors. Hence, this technical note presents findings from a study that reviewed the existing literature to determine if a correlation exists between the number of test data available and the choice of the uncertainty factors related to the test data (β_{TD}) and modeling (β_{MDL}), as well as to assess if there exists a trend in the choice of beta factors for new structural systems.

As per FEMA P695, the modeling uncertainty is related to the robustness of the numerical model and how well it predicts the collapse behavior. For a new lateral load resisting system, the behavior of the system is unknown until experiments are performed, and the numerical model used to predict collapse behavior depends on the availability of this experimental knowledge. As such, to some extent, the quality of the test data and the number of repeated results give confidence in the collapse behavior, which can then be utilized to compare/validate the model's output. Therefore, the current study tries to understand if there is an indirect correlation between the two.

Methodology

For the current study, 150 research publications related to FEMA P695 were found, covering the period 2009 to 2018. However, the full text was available for only 81 of them. Out of these, there were only 33 were cases in which the reporting authors actually had to make decisions regarding the quality rating values. These 33 references relevant to the current study are listed in Table 1, along with the test data (β_{TD}) and modeling (β_{MDL}) uncertainty factor ratings reported.

Note that studies for which the uncertainty values were chosen based on recommendations from another study were not considered as a part of the 33 studies listed in this study. For example, recent studies on seismic isolation systems (Kitayama and Constantinou 2018; Shao and Mahin 2020) directly used the uncertainty values

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Table 1. Quality rating for 33 studies

Serial number	Authors	Material used	β_{TD}	β_{MDL}	Number of test data[a]
1	Zareian et al. (2010)	Steel	Good	Good	300
2	Filiatrault and Christovasilis (2010)	Wood	Good	Good/ poor	—
3	Richard et al. (2010)	Concrete	Good	Good	—
4	Chen (2010)	Steel	Good	Good	—
5	Sato and Uang (2013)	Steel	Superior	Good	9
6	Vigh et al. (2013)	Steel	Fair	Good	44
7	Farahi and Mofid (2013)	Steel	Fair	Good	—
8	Shamim and Rogers (2015)	Steel	Good	Good	10
9	Purba and Bruneau (2015)	Steel	Fair	Good	36
10	Gogus and Wallace (2015)	Concrete	Good	Good	—
11	Lee and Kim (2015)	Concrete	Poor	Good	—
12	Donovan and Memari (2015)	Others[b]	Fair	Fair	—
13	Elkady and Lignos (2015)	Steel	Good	Good	7
14	Jayamon et al. (2015)	Wood	Good	Poor	—
15	Masroor and Mosqueda (2015)	Steel	Good	Good	—
16	Nicknam (2015)	Concrete	Fair	Fair	—
17	Siyam et al. (2016)	Concrete	Fair	Fair	6
18	Koliou et al. (2016)	Concrete	Fair	Fair	—
19	Kuyilmaz and Topkaya (2016)	Steel	Superior	Superior	—
20	Ezzeldin et al. (2016)	Masonry	Good	Good	4
21	Gencturk et al. (2016)	Others[b]	Good	Good	—
22	Judd and Charney (2016)	Steel	Fair	Fair	—
23	Nobahar et al. (2016)	Steel	Fair	Good	—
24	Zsarnoczay and Vigh (2017)	Steel	Good	Good	—
25	Bezabeh et al. (2017)	Others[b]	Fair	Fair	—
26	Choi et al. (2017)	Steel	Fair	Fair	—
27	Lu et al. (2017)	Concrete	Good	Good	—
28	Fiorino et al. (2017)	Steel	Good	Good	12
29	Kechidi et al. (2017)	Steel	Good	Good	109
30	Sarti et al. (2017)	Wood	Fair	Good	21
31	Sadeghi and Rofooei (2018)	Steel	Superior	Good	—
32	Aly et al. (2020)	Concrete	Good	Good	—
33	Hsiao et al. (2013)	Steel	Good	Good	80

[a]Number of test data used to validate the nonlinear numerical model.
[b]Other materials, namely, engineered cementitious composite (ECC), structural insulated panel (SIP), and hybrid systems.

recommended by FEMA P695 (FEMA 2009; Masroor and Mosqueda 2015). Therefore, these studies (Kitayama and Constantinou 2018; Shao and Mahin 2020) were not included in Table 1, while the study by Masroor and Mosqueda (2015) was included.

One of the initial objectives of the study was to investigate whether there was a correlation between the total number of tests having been performed on given lateral-load resisting systems over time and their assigned uncertainty rating, but that number of tests was typically not reported. Therefore, it was decided instead to use the number of test data specifically considered for the validation of the numerical model in these studies. This shift in logic is schematically illustrated in Fig. 1. Beyond this simplification, it was further found that not all researchers specifically listed the number of test data used to validate the model used in their study. When that information was missing, attempts were made to obtain the total number of tests by reviewing the experimental studies conducted by the cited authors. Out of this process, that information was obtained for only 12 studies, which are listed in Table 1.

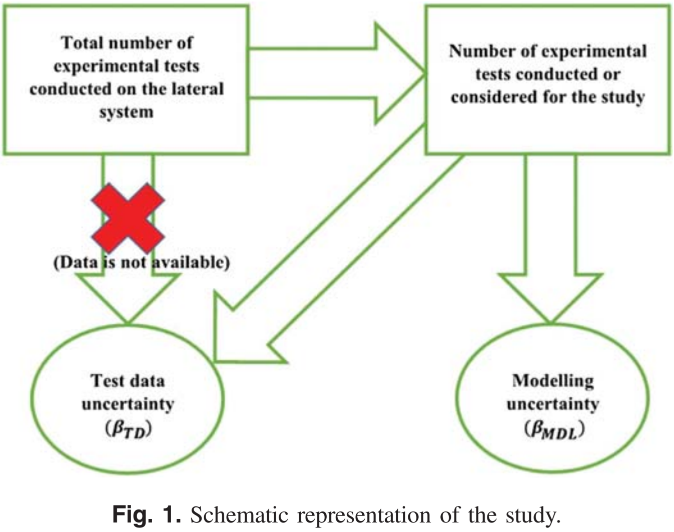

Fig. 1. Schematic representation of the study.

Results and Observations

Initially, it was assumed that a lateral-load resisting system that has received more experimental scrutiny—which can be achieved in one way by having been the subject of many experiments over many years—would have less uncertainty. In other words, it was anticipated that the extent of test data could be directly proportional to the resulting quality rating. To verify this assumption, the data shown in Table 1 were collected and analyzed. It can be seen that out of the 12 studies in Table 1 for which the number of experiments considered was reported, only one study indicated a *superior* quality rating. In that study, although only nine tests' data were used for

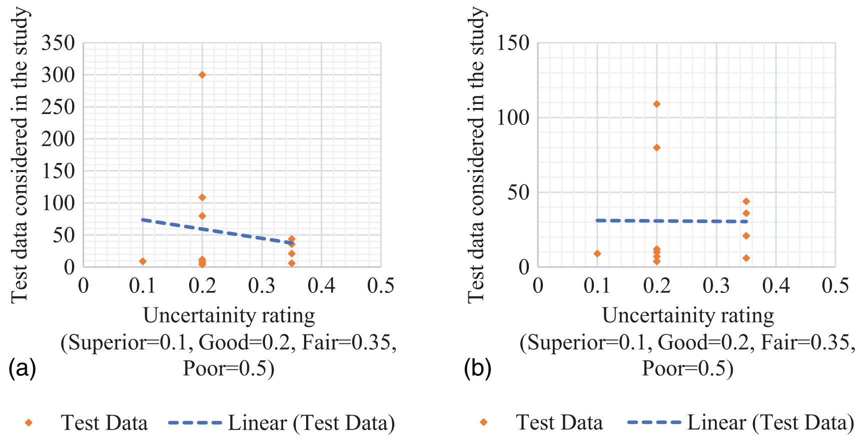

Fig. 2. Number of test data considered in the study versus test data uncertainty: (a) all studies considered; and (b) excluding (Zareian et al. 2010).

calibration of the numerical model, it was argued that all the tests showed a consistent behavior and energy dissipation mechanism (Sato and Uang 2013).

Out of the remaining 11 studies (with the number of test data) included in Table 1, 7 used *good* quality ratings, and the rest used *fair* quality ratings. Further, it can be seen from Table 1 that even with a large number of test data, researchers have generally chosen a quality rating of *good* over *superior*. It could be speculated in this study that this choice of a lower quality rating could be driven by either a shortage of test data for some loading scenarios, or not being able to capture a particular mode of failure or the challenge of having absolute confidence in nonlinear modeling (particularly in light of findings from blind-predictions of experimental results).

In order to investigate whether a correlation exists between the total number of tests and the uncertainty factors related to the test data, the information presented in Table 1 is plotted, as shown in Fig. 2(a). It can be observed from the data set that one of the data points can be considered as an outlier as it is too large when compared to the other values in that set. In order to look at the sensitivity of the correlation, the linear regression plots for the data set with and without the outlier points (i.e., 300 tests) are plotted in Figs. 2(a and b), respectively. Comparing the two figures, and in the absence of more data points, it can be said that the trend in this study is highly sensitive to a single outlier data point.

However, what can be ascertained from the data in Table 1 is that even with few test data, some researchers were confident to assign higher test data quality ratings on the assertion that the tests conducted were able to capture all failure modes effectively. Further, as stated in FEMA P695, the test data uncertainty would depend on "the completeness and robustness of the overall testing program and the confidence in the test results." From Table 1, it is also seen that generally, in most studies, ratings were dominantly good, often fair, and never poor.

Similarly, the correlation between the test data used to validate the model with the modeling related uncertainty was also studied. It was observed that all but one of the studies rated the modeling related uncertainty as good (the other one was labeled fair). This trend might be attributed to the fact that FEMA P695 recommends using the rating good if "the nonlinear models were able to capture most, but not all, nonlinear response mechanisms leading to collapse or the complete design space is not fully represented such that there is only a reasonable confidence that the range of response captured by the models is indicative of the primary structural behavior characteristics that affect collapse." This seems to suggest that most researchers share this restrained but generally positive confidence in the adequacy of nonlinear hysteretic models in modern inelastic analysis. Therefore, in this case, the trend might not be that meaningful in light of the near unanimous use of the good rating used throughout almost all studies (and are not plotted in this study).

In order to understand whether the type of material used for construction has any influence on the choice of a quality rating of a lateral load resisting system, the number of times each quality rating has been used for structural systems having specific material types are presented in Figs. 3(a and b) for the 33 studies mentioned in Table 1. It can be observed that lateral systems made of steel have been the subject of more FEMA P695 studies, followed by concrete,

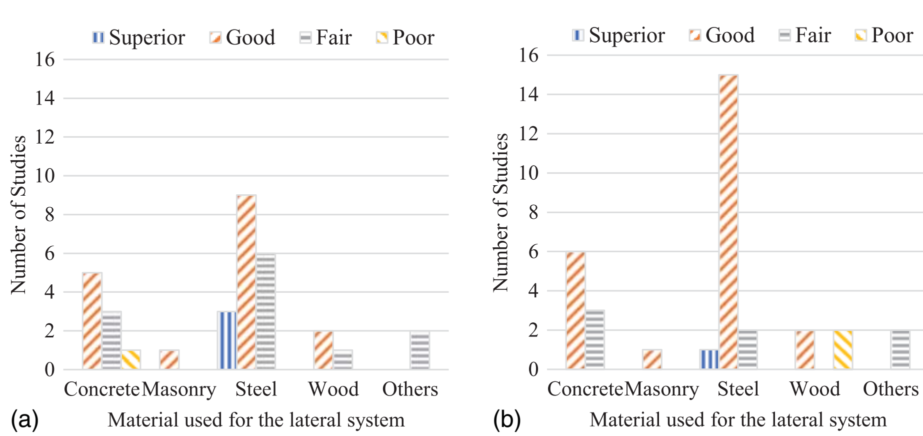

Fig. 3. (a) Number of studies with a β_{TD} versus material used in 33 studies; and (b) number of studies with a β_{MDL} versus material used in 33 studies.

Table 2. Comparison of data from NIST GCR 10-917-8 with results from this study

Serial number	Type	Detailing	NIST data β_{TD}	NIST data β_{MDL}	Current study data β_{TD}	Current study data β_{MDL}
1	RMSW	SPECIAL	Good	Good	Good	Good
2	RMSW	ORDINARY	Fair	Good	—	—
3	RCSW	SPECIAL	Good	Good	Good	Good
4	RCSW	ORDINARY	Good	Good	Good	Good
5	SCBF	SPECIAL	Good	Good	Good	Good
6	BRBF	N/A	Good	Good	Good	Good
7	SMF	SPECIAL	Good	Good	Good	Good
8	RCMF	SPECIAL	Good	Good	—	—
9	RCMF	ORDINARY	Good	Fair	—	—
10	SMF	SPECIAL	Good	Good	—	—
11	WLFSW	N/A	Good	Good/poor	Good	Good/poor

Note: N/A = not applicable; RMSW = reinforced masonry shear wall; RCSW = reinforced concrete shear wall; SCBF = special steel concentrically braced frame; BRBF = buckling-resistant braced frame; SMF = steel moment frame; RCMF = reinforced concrete moment frame; and WLFSW = wood-light frame shear wall.

wood, masonry, and other materials [namely, engineered cementitious composite (ECC), structural insulated panel (SIP), and hybrid systems]. This data also illustrates that the uncertainty rating associated with the studies done on steel structures is typically better than those for the other building materials. As shown in Fig. 3(a), three studies used the superior index for steel structures, while no studies did when other materials were used. It is speculated that this is attributed to a belief across the research community that the nonlinear inelastic behavior and properties of steel lateral systems, and their failure modes, are better understood than those of other materials. Nonetheless, it remains that, across all studies, good was the most frequently used index, particularly for steel and concrete.

In parallel with the development of the FEMA P695 study, the National Institute of Standards and Technology (NIST) led a study to test the methodology with a number of seismic structural systems that were already part of existing building codes and seismic design specifications. The results presented in Table 1 for the 33 studies representing different lateral systems were compared with the data obtained from the Section 8.4.2 of NIST GCR 10-917-8 document (Kircher et al. 2010).

It was observed that out of the 11 types of systems mentioned in the NIST document, 7 of them were included in the preceding data set of 33 studies. Although the sources consulted here (i.e., research publications) for these data were different from those of the NIST report, the reported beta factors were evidently the same, as shown in Table 2. Most importantly, the studies reported in the NIST document do not explicitly refer to the number of test data used for validation. Hence, the trend presented in this study could not be verified against the NIST study results.

The NIST report indicated the following: "Many trial applications noted the subjective nature of the quality ratings used to define uncertainty associated with design requirements, test data, and nonlinear modeling." It also expressed the following concern: "There is a need for a consistent and reliable method for selection of quality ratings and a fair assessment of the quality of design requirements, test data, and nonlinear modeling capabilities across all systems. The methodology recognizes this need, and control occurs through review and concurrence in the peer review process." This is consistent with the observations made as part of the current study because, as it stands, quality ratings apparently tend to gravitate toward *good*.

Conclusions

A review of data from the existing literature on past FEMA P695 studies was conducted to assess if there exists a trend in the choice of uncertainty factor ratings related to the test data and modeling for new structural systems. Information collected showed that uncertainty factor ratings related to the test data have generally not been proportional to the number of test data conducted (which would seem counterintuitive to the initial assumption). Further, based on FEMA P695, the modeling uncertainty factor rating depends on how well the nonlinear models represent the behavior and associated failure modes of the lateral load resisting system under consideration. From this perspective, findings from the literature review reveal a strong bias in past studies toward the good rating, which reinforces the previously expressed belief that there exists a need for a method to more rigorously determine quality ratings. Results also show that the uncertainty factor ratings associated with test data and modeling are typically better for steel structural systems compared to other building materials.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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